5-2021

Seeding Rate, Herbicide, and Irrigation Effects on Spring-Seeded Oat-Alfalfa Companion Crops

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SEEDING RATE, HERBICIDE, AND IRRIGATION EFFECTS ON SPRING-SEEDED

OAT-ALFALFA COMPANION CROPS

by

Carson D. Roberts

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Plant Science

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UTAH STATE UNIVERSITY
Logan, Utah

2021

ABSTRACT

Oat-Companion Seeding Rate, Herbicide, and Irrigation Effects

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By

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Utah State University, 2021

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Small grain companion crop seeding rate recommendations for alfalfa (*Medicago sativa* L.) establishment are dated and inconsistent, and how a small grain companion crop seeding rates should be adjusted at different moisture levels is unknown. A study was conducted to provide clarity about oat (*Avena sativa* L.) companion crop seeding rates that maximize weed suppression and forage yield and minimize the effect on alfalfa stand establishment. This experiment considered oat companion crop seeding rates at various irrigation levels. Companion crop treatments consisted of oats sown at 89, 45, 22, 10, and 0 (with and without herbicide) kg ha^{-1}. Irrigation was applied using a line-source irrigation gradient with five irrigation levels (IL). The largest amounts of water were applied at high ILs, and low ILs received lower amounts of water. At the two highest ILs in the first cut, a 2-fold increase in alfalfa stem density occurred as the 89 kg ha^{-1} oat rate was reduced to 11 kg ha^{-1}, but at the lowest two ILs, the increase was 5 to 7-fold. Similarly, second cut differences in stem density were only apparent at lower ILs. First cut forage yields were lowest in 0 kg ha^{-1} treatments and increased with increasing oat seeding rates. These differences in yield were amplified as ILs were reduced. At high ILs, oats sown with alfalfa increased yield over the control by less than 30%, but total yield was increased by approximately 60% in the lowest ILs. Conversely, yields were highest among 0 kg ha^{-1} treatments in second cut. At both cuts, herbicide and untreated plots produced the largest alfalfa yields, and alfalfa yield was reduced as oat seeding rates were increased. The highest oat seeding rates (89 and 45 kg ha^{-1}) reduced weed dry matter yield to levels comparable to the herbicide in both cuts. Generally, the presence of oats or weeds reduced crude protein. NDF was also less desirable at first cut with increasing oat seeding rates, and differences in NDF increased as irrigation was reduced. Results observed in this study suggest that the highest alfalfa density, yield, and forage quality can be achieved when alfalfa is sown alone with a herbicide. If herbicides cannot be used, the best results may be achieved when alfalfa is sown with a companion crop when irrigation is high, but without a companion crop when irrigation is low. Seeding rates between 22 and 11 kg ha^{-1} may be most desirable when a companion crop is used.

(67 pages)

PUBLIC ABSTRACT

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Small grain companion crop seeding rate recommendations for alfalfa (*Medicago sativa* L.) establishment are dated and inconsistent, and how a small grain companion crop seeding rates should be adjusted at different moisture levels is unknown. A study was conducted to provide clarity about oat (*Avena sativa* L.) companion crop seeding rates that maximize weed suppression and forage yield and minimize the effect on alfalfa stand establishment. This experiment considered oat companion crop seeding rates at various irrigation levels. Companion crop treatments consisted of oats sown at 89, 45, 22, 10, and 0 (with and without herbicide) kg ha^{-1}. Irrigation was applied using a line-source irrigation gradient with five irrigation levels (IL). The largest amounts of water were applied at high ILs, and low ILs received lower amounts of water. At the two highest ILs in the first cut, a 2-fold increase in alfalfa stem density occurred as the 89 kg ha^{-1} oat rate was reduced to 11 kg ha^{-1}, but at the lowest two ILs, the increase was 5 to 7-fold. Similarly, second cut differences in stem density were only apparent at lower ILs. First cut forage yields were lowest in 0 kg ha^{-1} treatments and increased with increasing oat seeding rates. These differences in yield were amplified as ILs were reduced. At high ILs, oats sown with alfalfa increased yield over the control by less than 30%, but total yield was increased by approximately 60% in the lowest ILs. Conversely, yields were highest among 0 kg ha^{-1} treatments in second cut. At both cuts, herbicide and untreated plots

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ACKNOWLEDGMENTS

I would like to extend sincere appreciation to all those who helped with this project. This research would not have been possible without all those who offered their assistance, especially during times of harvest and data collection. I would also like to thank Dr. Joseph Robbins for being so willing to assist in the data analysis and writing process.

Above all, I would like to thank Dr. J. Earl Creech and my wife, Madi. Dr. Creech has played a key role in teaching me about proper research and writing techniques. His wisdom and experience have been priceless. At all times during this process, Madi's positivity and encouragement has helped keep my passion for this work alive.

Carson D. Roberts

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ALFALFA ESTABLISHMENT AND COMPANION CROPS IN THE INTERMOUNTAIN WEST: A REVIEW OF LITERATURE

1 | ALFALFA HISTORY AND APPLICATION

Alfalfa (*Medicago sativa* L.) is cultivated as a forage crop throughout the world and is the only forage crop that was cultivated before recorded history (Bolton, J.L. 1962). Alfalfa seed was transported from its believed origin in the Middle East to Greece during the 4th century B.C., then to Rome during the 2nd century B.C. as a horse feed. It was also transported from Turkestan to eventually be grown in China by 126 B.C. The crop spread through Europe from the 16th to 18th centuries. It was transported to the Americas by the Spanish and Portuguese in the 16th century (Bolton, Goplen, & Baenziger, 1975). From Mexico, alfalfa seed was transported to present-day United States in the late 1840's or early 1850's to be grown in California, New Mexico, and Arizona. Seed was then transported to Utah shortly afterward where it grew well due to its adaptation to the climate (Bolton, 1962). However, Brough, Robison, and Jackson, (1977) disagree with the common assumption that Utah alfalfa was transported mainly from California of Spanish origin. They submit that there are records of alfalfa being transported by pioneers from the British Isles to Utah, and that the main origin of early alfalfa production was from that area.

Modern varieties have been developed to increase hardiness, yield, and quality. In 2011 glyphosate resistant alfalfa varieties were permanently made available to growers.

This technology allows growers to apply glyphosate as a foliar to nondormant alfalfa at any growth stage with little to no injury (Orloff, & Putnam, 2011). Both conventional and genetically altered alfalfa varieties are grown in Utah depending on the producer's preference.

Alfalfa has been grown as a crop in Utah since the earliest settlers arrived in the 1850's. Well-drained soils that are not prone to flooding or high water tables, warm days and cool nights during the growing season, and relatively low humidity levels make Utah and the surrounding western states, which comprise the Intermountain West, very suitable to growing and harvesting alfalfa. Because of its adaptation, alfalfa has become a major economic driver in Utah agriculture, and in 2020 alfalfa was valued at $386.6 million with over 222,000 hectares devoted to the crop (USDA Census of Agriculture, 2020). Alfalfa is an important feed for most classes of livestock in Utah, and, in many cases, the primary dietary supplement. Production methods are similar among producers throughout the state. Most alfalfa in the area is sown in the spring or fall using a drill in conventionally tilled, irrigated fields following corn or small grains in rotation. Varieties sown depend on the local climate, management techniques, and personal preferences of the grower. Alfalfa is usually harvested two to three times during the establishment year and three to five times per year thereafter in most Utah alfalfa production areas depending on the location and planting date.

2 | ALFALFA ESTABLISHMENT

Management practices that allow for maximum seed emergence and survival are essential for establishing a long-lived, productive alfalfa stand. Because it is a small-seeded crop, alfalfa has relatively low seedling vigor. Environmental conditions during the seedling year, such as weed density, soil erosion, and inclement weather or moisture can reduce the plant density of the alfalfa stand. Irrigation, planting methods, and weed control are all components of good alfalfa stand establishment.

2.1 | Soil Moisture

Precipitation in the Intermountain West is limited; therefore, irrigation is commonly used to compensate for low soil moisture. Irrigated alfalfa accounts for 32% of the land area in agricultural production in the state of Utah (USDA Census of Agriculture, 2018). Approximately 188,900 hectares of alfalfa are irrigated, 11,100 hectares are partially irrigated, and 10,501 hectares of alfalfa are non-irrigated. In many parts of Utah inconsistency of irrigation and water shortages result in reduction in the amount of water applied to crops. Adequate soil moisture availability during alfalfa stand establishment is critical to the delicate nature of developing seedlings. Many factors that influence water use in alfalfa include climate, elevation, growing season length, number of cuttings, latitude, alfalfa variety, soil properties, and other site-specific factors. Research has shown that there is, to a certain extent, a positive linear alfalfa yield response to the amount of water applied (Orloff & Putnam, 2013). Research in southern Idaho estimated that 14 cm of irrigation water was required to produce 1000 kg of alfalfa hay at 12% moisture (Wright, J.L. 1988). Another study concluded that 21 cm of evapotranspiration are required to produce 1000 kg of alfalfa (Lindenmayer, Hansen, Brummer, & Pritchett, 2011).

Alfalfa is considered very drought tolerant (Frate, Roberts, & Marble, 1991). Water can be pulled from depths of up to 2 m deep by mature alfalfa depending on soil root limiting layers. However, up to 70% of alfalfa's water uptake comes from the top 0.60 m of soil regardless of the depth of the taproot (Hagood, 1970). A larger population of lateral roots, which are primarily responsible for the uptake of water and nutrients, in that zone is the most likely cause of larger water uptake. More lateral roots develop as alfalfa plants reach maturity, therefore, water use efficiency can be maximized as an alfalfa stand ages (Lindenmayer et al., 2011). Findings by Thomas, and Hill, (1949) and Brown, Pearce, Wolf, and Blaser, (1972) suggest that an average of 84% of fixed CO_2 is devoted to above-ground growth during the second year of alfalfa production, compared to only 59% during the first production year. Lindenmayer et al. (2011) observed that most of the carbon not devoted toward shoot and leaf development goes toward root development. Since water is a necessary component of photosynthesis, water reductions during alfalfa establishment could cause irreparable damage to the development of seedling root systems (Rumbaugh, Asay, & Johnson, 1984).

Soils should be moist when alfalfa is sown and should continue to be moist through emergence. Many Utah alfalfa stands are established during spring to take advantage of spring rain to assist with emergence. When additional moisture is needed after planting, light irrigation events are recommended to reduce damage from anerobic conditions and erosion. Alfalfa has a relatively shallow rooting depth as a seedling following emergence. Adequate soil moisture levels should be maintained as seedlings grow towards establishment.

2.2 | Planting Methods and Considerations

Moisture is not the only concern when it comes to successfully establishing alfalfa. Stand establishment can also be affected by factors such as site selection, seedbed preparation and fertility, planting date, seed placement and rate, and weed control.

Fields selected for alfalfa production should have conditions conducive to alfalfa growth. Extension recommendations suggest that fields should be free from root restricting layers, as alfalfa will not grow properly unless ample soil depths can be reached (Putnam, Mueller, Frate, Canevari, & Orloff, 2012). Restricting layers include compaction, hardpan, water tables, and herbicide residual. Fields should also be avoided if seasonal water-logging is common. Herbicide labels should be reviewed if residual from previous applications is expected. Fields with relatively low salinity levels are better for alfalfa production. Alfalfa is considered moderately sensitive to salinity with an electrical conductivity of the saturated extract (ECse) threshold of 2.0 (Havlin, Beaton, Tisdale, & Nelson, 2013). They also suggest that 7.3 percent yield decrease per unit of ECse can be expected in saline environments. Fields should also be free from the risk of autotoxicity or allelopathy from the previous crop. Mature alfalfa can exude toxicity in the rhizosphere that disallow the survivability of seedling alfalfa (Cosgrove, & Undersander, 2003). Rotating to an alternative crop for at least one growing season can disrupt pest cycles, reduce the risk of autotoxicity, and reduce competition from weeds. Other crops, including rye and triticale, can have an allelopathic effect on small-seeded plants including alfalfa. If alfalfa is to be sown in rotation after crops with an allelopathic effect, tillage may help reduce the risk of injury (Adhikari, Mohseni-Moghadam, & Missaoui, 2018).

Poorly prepared seedbeds can result in reduced alfalfa emergence (Tesar & Marble, 1998). The best conditions for planting alfalfa include a moist, firm, consistent, clod-free seedbed. Good seedbeds can be achieved by conventional tillage that are finished by using a harrow, roller, or cultipacker (Shewmaker, & Cheyney, 2007). While preparing a seedbed, soil fertility should be considered. Approximately 35 kg of nitrogen, 7 kg of phosphorus (P_2O_5), and 25 kg of potassium (K_2O) can be removed with each metric ton of alfalfa (Brown Fransen, Horneck, Koenig, Peterson, Platt, & Stevens, 2009). If fertilization is neglected, soil nutrients can easily be depleted. Nitrogen applications are not necessary if seed is inoculated with the correct rhizobia bacteria, and the levels of nitrogen in phosphorus fertilizer are generally sufficient to supplement seedlings until rhizobia can develop. Most seed is sold pre-inoculated. Applications of phosphorus and potassium fertilizers should be performed according to recommendations from soil tests. Fertilizer applications should take place prior to planting, and fertilizers should be incorporated into the soil. Phosphorus can be applied in a starter band during planting. Little to no potassium should be applied in a starter band due to high salt levels. If potassium rates in excess of 220 kg K_2O ha^{-1} are needed, applications should be split between spring and fall (Havlin et al, 2013).

Planting dates vary throughout Utah depending on the climate and elevation. Seedlings can be killed by frost when temperatures are at or below 3.3°C for more than 4 hours (Teutsch, Henning, Smith, Keene, & Dixon, 2017). In general, it is suggested that spring seeded alfalfa be planted around April, when temperatures are cool but not too cold and the high temperatures of summer have not yet arrived. When alfalfa is planted in the fall, sowing should occur 4-6 weeks prior to 50% chance of a killing frost

(Undersander et al., 2011). For most of Utah, fall alfalfa establishment is most successful when planted before September 1.

Planting depths should be between 0.6 and 1.9 cm for the best emergence. Seeding depths can be increased in sandy soils to reach water resources (Tesar, & Marble, 1998). Seeding rates for acceptable alfalfa seed can depend on planting method and field conditions. For conventional drills, rates can be between 17 and 22 kg ha^{-1}, and should be increased to between 22 and 28 kg ha^{-1} for spin or drop broadcast seeders (Putnam et al., 2012). They also suggest that seeding rates can be lowered to 13 to 17 kg ha^{-1} under excellent field conditions where soil is firm and moist. Seeding implements should be checked prior to planting to ensure that accurate, consistent seed placement will occur. With any seeding method, good seed-to-soil contact is paramount in achieving good alfalfa emergence.

2.3 | Weed Control

Weed Control during alfalfa establishment is one of the most important concerns for farmers in Utah. Weeds decrease forage quality and lower the economic value of the hay. Weeds are a known to increase seedling mortality, therefore, reducing the yield potential during the life of the stand (Canevari, Vargas, & Orloff, 2009). Permanent damage to an alfalfa stand can occur when alfalfa seedlings compete with weeds.

Herbicides are the most common and effective method of controlling weeds. Herbicides used for conventional alfalfa stand establishment are limited and require progressive management to avoid injury to the alfalfa stand. S-ethyl dipropylthiocarbamate (Eptam) and N-butyl-N-Ethyl-a,a,a-trifluoro-2,6-dinitro-p-toluidine (Balan) are two pre-plant herbicides that can control many grass and broadleaf weeds. Preplant herbicides must be incorporated before planting and may not control all weeds. Using a post-emergence herbicide can be advantageous because specific emerged weeds can be targeted, and the best herbicide can be utilized (Canevari et al., 2009). Paraquat dichloride (Gramoxone), Octanoic acid ester of bromoxynil (buctril), 2-[1-(ethoxyimino)butyl]-5-[2-(ethythio)propyl] -3-hydroxy-2-cycIohexen-l-one (sethoxydim), 2-[(*E*)-*N*-[(*E*)-3-chloroprop-2-enoxy]-*C*-ethylcarbonimidoyl]-5-(2-ethylsulfanylpropyl)-3-hydroxycyclohex-2-en-1-one (clethodim), 2,4-dichlorophenoxy butyric acid (2,4DB), ammonium salt of imazethapyr: (±)-2-[4,5-dihydro-4-methyl-4- (1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid (pursuit), and ammonium salt of imazamox: 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)- 5-oxo-1 H-imidazol-2-yl)-5-(methoxymethyl)-3-pyridinecarboxylic acid (raptor) are some herbicides that can be effectively used after emergence. Grass herbicides for use in alfalfa include: Sethoxdim, clethodim, paraquat, imazethapyr, and imazamox. Broadleaf herbicides include: Paraquat, bromoxynil, 2,4DB, imazethapyr, and imazamox. Many of these post-emergence herbicides can cause damage to alfalfa seedlings. Herbicide Injury can be caused due to maturity, soil temperature, and humidity levels.

Glyphosate resistant (Roundup Ready®) genetics in alfalfa allow producers to effectively control weeds in alfalfa stands at any seedling growth stage without injury during the seedling year (McCordick, Hillger, Leep, & Kells, 2008). Planting glyphosate resistant alfalfa can also allow glyphosate to be used during the life of the stand whenever chemical control is required; however, mature stands can experience injury in the Intermountain West under certain conditions (Loveland, Creech, Yost, & Samac, 2020).

3 | ALFALFA COMPANION CROPPING

Historically, establishing alfalfa with a companion crop was common, but with the advent of herbicides, use of companion crops dwindled (Tesar, & Jackobs, 1972). However, new marketing opportunities (such as organic and oat-alfalfa mixed hay), onset of herbicide resistant weeds, interest in cover crops and soil health, and need for emergency forage, have caused renewed interest in alfalfa companion cropping. Companion crops are often sown with alfalfa during establishment with a goal to mitigate some of the challenges associated with establishment. These challenges include first-year yields, weed control, and erosion control. Companion crops are unappealing in many instances because they compete for moisture, light, and nutrients just like weeds. Companion crop type, companion stature, crop harvest timing, and seeding rates of the companion crop have been studied to find the best management practices for companion crops.

3.1 | Companion Species

Many different plants have been considered to assist in alfalfa establishment. The main idea is to use a cultivar that is quick to establish, short in stature, early- to mid-maturing, and small leaved. The chosen cultivar should also be harvestable and marketable. One study conducted in Minnesota analyzed oats (*Avena sativa* L.), wheat (*Triticum* L.), barley (*Hordeum vulgare* L.), flax (*Linum usitatissimum* L.), field pea (*Pisum sativum* L.), brassica, and annual ryegrass (*Lolium multiflorum* L.) (Sheaffer, Martinson, Wyse, & Moncada, 2014). Field pea, annual ryegrass, and the control produced the lowest yields in the following year compared to the other companion crop treatments. They observed that oat, wheat, and barley reduced weeds more effectively than any of the other treatments. This study also found that wheat, barley, and oat were the best options as a companion crop for their ability to control weeds and increase economic returns. In Wisconsin, oat and barley were mixed with pea as a companion crop to alfalfa (Chapko, Brinkman, & Albrecht, 1991). They found that barley and pea mixtures produced the highest yield. It was concluded, however, that oat and pea mixtures were the best options due to the increase in forage quality. Another study evaluated different annual ryegrass cultivars as alfalfa companion crops compared to oats as a standard (Sulc et al., 1993). Annual ryegrass cultivars that showed low persistence after the first harvest produced the best alfalfa yields and persistence. Annal ryegrasses that had some fall growth and perennial characteristics had the most detriment to alfalfa stand persistence by reducing alfalfa plant densities. When compared to the ryegrass treatments, oats produced higher alfalfa plant density and yield. Oat is the most common choice as a companion crop because of its potential as a forage, comparatively short stature, and quick establishment (Lanini, Orloff, Vargas, Orr, Marble, & Grattan, 1991).

3.2 | Harvest Timing

Small grain companion crops have been harvested for mature grain in the past. This practice has proved to be detrimental to alfalfa stand density. Alfalfa stand establishment is most successful when the companion crop is harvested as hay or silage instead of grain and straw. (Brink & Marten, 1986). Similar observations were made in Wisconsin where it was observed that harvesting oats at maturity drastically reduced soil moisture and alfalfa stand densities (Klebesadel & Smith, 1960). They found when oats were in the soft dough stage the highest protein and dry matter yields were observed. Oats harvested in the soft dough stage were recommended, because they maximized yield, nutritive value, and reduced oat regrowth. Both studies observed that clipping the crop earlier than the boot stage can result in reduced carbohydrate storage in alfalfa plants for regrowth following the first harvest, so earlier clippings have not been recommended. Harvesting oats at early stages can also result in undesirable regrowth of the oat companion crop.

3.3 | Alfalfa Companion Crop Seeding Compared to Solo Seeding

There are advantages and disadvantages associated with both solo-seeding and using companion crops for alfalfa establishment. Both herbicide applications and oat companion cropping are often considered better alternatives to neglecting to control weeds. It is, however, possible that companion crops have a similar effect on alfalfa stand establishment as weeds. In Iowa, it was observed that treatments without oats produced better stand densities compared to where weeds were present in solo-seeded alfalfa (Hoy, Moore, George, & Brummer, 2002). Peters (1961) observed that alfalfa density and yield can be impacted in subsequent years by using a companion crop. Yet, in California densities were higher among treatments at low oat rates the year following establishment than in clear seedings (Lanini et al., 1991). It is possible that growing conditions can impact the level at which oats compete with alfalfa. Competition has been observed when soil moisture is suitable for growth of the crop (Sulc, Albrecht, & Casler, 1993).

3.4 | Using Herbicides to Terminate Oats Prior to Harvest

Weed control, soil erosion, and soil crusting are challenges common in alfalfa establishment and first-year production. Selective grass-control herbicides have been utilized to terminate oat, barley, and wheat companion crops following alfalfa emergence. This was primarily done to eliminate the need of a herbicide prior to alfalfa canopy closure, and as a way to avoid the negative effects of companion crops while benefiting from reductions in soil erosion and crusting (Stute & Posner, 1993). Curran, Kephart, and Twidwell, (1993) evaluated the chemical removal of the oat crop at heights of 5 cm and 15 cm compared to traditional companion cropping and clear-seeded alfalfa. This study found that termination of the oat crop at the 5 cm stage produced higher alfalfa yields than at the 15 cm stage. Both treatments produced higher alfalfa production than treatments where the crop was clipped at the boot stage. Termination of the oats at the 5 cm stage occurs before alfalfa emergence and may not provide sufficient cover or mitigate erosion.

Glyphosate- resistant (GR) alfalfa has added flexibility and ease to controlling weeds during establishment, but erosion continues to be an issue while alfalfa seedlings are small. Traditionally, the timing of the application of glyphosate in a clear-seeded environment occurs between the 3 and 6 trifoliate alfalfa stage (McCordick et al., 2008). This practice usually provides the best weed control and removes any alfalfa that did not contain GR traits. Some producers have coupled companion crops with GR technology with the intent to terminate the companion crop prior to the first cut. Further work is needed to provide in-depth information on the best stage to chemically terminate an oat companion crop in GR systems.

3.5 | Oat Companion Crop Forage Nutritive Value

Forage quality can also be a factor when deciding if an oat companion crop should be used. In general, clear-seeded alfalfa during the establishment year has exceptional quality (Becker, R.L., Sheaffer, C.C., Miller, D.W., and Swanson, DR. 1998). However, the presence of a companion crop can diminish the high-quality characteristics of seedling alfalfa. In Iowa (Hoy et al., 2002) found that oat companion crops reduced crude protein (CP) and in vitro dry matter digestibility and increased neutral detergent fiber (NDF) during the first cut. The inverse occurred, though, during subsequent cuttings as CP was lower and NDF was higher among treatments where companion crops were not present. Both Hoy et al., (2002) and Brothers, Schmidt, Kells, and Hesterman, (1994) reported that there were no differences in quality in years following establishment. Chapko et al. (1991) and Hall, Curran, Werner, & Marshall (1995) found that neglecting to control weeds during establishment can reduce quality, because reduced stand density at establishment allow space for weeds to grow in following years. Stute and Posner, (1993) suggest that using a herbicide such as sethoxydim to control broadleaf weeds can further increase quality in companion crop stands.

3.6 | Companion Crop Seeding Rates

Oat rates have been studied to find the best management practices for companion cropping. Selecting the correct seeding rate can be challenging; the chosen rate should balance the need for maximum forage yield and weed suppression while causing minimal harm to the alfalfa. During the early and mid-1900's, oats have been sown with barley at a standard rate of 56 to 84 kg ha^{-1} (Peters, 1961). More recent studies have suggested that lower oat rates produce the best results when balancing weed control, yield, and alfalfa establishment. Studies by Lanini et al. (1991) in California found that forage yields for differing oat rates were equal among all treatments. It was observed that lower oat rates produced more tillers, and higher oat biomass. Where oats were present at any rate, the alfalfa and weed yields were reduced. Stand density was also reduced during establishment while using oats. Rates of 18 kg ha^{-1} were considered best to reduce weeds and build yields. Studies by Smith, Lowe, Strommen, and Brooks (1954) produced findings that suggest that decreased oat seeding rates will reduce the risk of establishment failure if underlying conditions such as moisture stress are present. General observations from both studies suggest that alfalfa recovered from the impacts of companion cropping more favorably when the growing conditions favored alfalfa. Yield was expected to be decreased for the life of the stand if there is too much stress on the crop. Both agree that there are advantages to solo-seeded alfalfa compared to planting alfalfa with a companion crop.

A great deal of variability exists in seeding rate recommendations in Extension publications across the western U.S. Some recommend seeding an oat companion crop at a relatively high rate of 39 to 56 kg ha^{-1} (Shewmaker & Cheyney, 2007; Undersander et al., 2011), while others have adopted lower seeding rates of 22 to 34 kg ha^{-1} (Dixon, Cash, Kincheloe, & Tanner, 2005; Islam, 2013; Putnam et al., 2012; Smith, Peairs, Beck, & Brown, 1996). Since the research on companion crop seeding rates is dated (most recent being 30 years old), and recommendations vary by state, additional research is needed to provide clarity on the oat companion crop seeding rates that maximize weed suppression and forage yield and minimize the effect on alfalfa stand establishment.

3.7 | Water Availability During Alfalfa- Oat Companion Crop Establishment

Companion crops compete with developing alfalfa seedlings for light, nutrients, and space, but competition for moisture is often the most concerning, particularly in semi-arid areas such as Utah. Mature alfalfa is very drought tolerant (Frate et al., 1991), and water use efficiency can increase as alfalfa stands age (Lindenmayer et al., 2011). However, seedlings are not drought tolerant, and reductions in water availability during establishment can reduce stand density (Rumbaugh et al., 1984). Some studies have reported that alfalfa is further suppressed by the presence of an oat companion crop when soil moisture is limited (Peters, 1961; Smith et al., 1954); however, it has also been observed that oats can cause more harm to seedling alfalfa at higher soil moisture levels due to competition for light (Janson & Knight, 1973). All the observations that have been recorded regarding companion crops and drought stress have been made based on comparisons between sites with differing moisture stress levels. No studies have compared alfalfa stand establishment with and without a companion crop at different irrigation levels in a single experiment.

Additionally, more work is needed to determine the optimal companion crop seeding rates at different levels of soil moisture. How the small grain seeding rate should be adjusted when used as a companion crop with alfalfa at different moisture levels is unknown. Competition between alfalfa seedlings and the companion crop may be more intense at higher seeding rates when moisture is limited. More research is needed to determine if seeding rate recommendations should vary based on expected available soil moisture.

4 | SUMMARY AND OBJECTIVES

Although interest in companion crops in alfalfa establishment is increasing most of the literature and management recommendations are outdated. Perhaps the least understood is how alfalfa sown with companion crop reacts to moisture stress, which is of special concern in the Intermountain West where precipitation and irrigation can often be limited. One solution may be to change the seeding rate of the companion crop based on moisture availability.

Additional information is needed to update USU management recommendations on companion crops, including when its use is justified, the correct seeding rates, and the best irrigation management practices. The objectives of this study were to determine the influence of oat companion crop seeding rates compared to the non-treated control (weedy and weed-free) at different irrigation levels on alfalfa stand establishment, weed suppression, and forage yield and nutritive value.

CHAPTER II

OAT-COMPANION SEEDING RATE, HERBICIDE, AND IRRIGATION EFFECTS ON SPRING-SEEDED ALFALFA

Abstract

Alfalfa (*Medicago sativa* L.) -oat (*Avena sativa* L.) companion crop seeding rate recommendations vary, and no recommendations exist for alfalfa-oat companion establishment in reduced moisture conditions. This study was conducted to offer updated information on optimal oat companion seeding rates for alfalfa establishment, depending on moisture availability. In this study, the effects of 0 (no oat seeding with and without 2,4D-B herbicide), 11, 22, 45, and 89 kg ha^{-1} oat companion seeding rates were evaluated under 5 irrigation levels (ILs) at North Logan, UT on a Millville silt loam (coarse-silty, carbonatic, mesic Typic Haploxeroll) in 2019 and 2020. At the two highest ILs in the first cut, a small, 2-fold increase in stem density occurred between 89 kg ha^{-1} and 11 kg ha^{-1} oat rate, but at the lowest two ILs, the increase was 5- 7-fold. Similarly, second cut differences in stem density were only apparent at lower ILs. First cut forage yields were lowest in 0 kg ha^{-1} treatments and increased with increasing oat seeding rates. These differences in yield were amplified as ILs were reduced. Conversely, yields were highest among 0 kg ha^{-1} treatments at second cut. The highest oat seeding rate and treatments where herbicide was applied had comparable weed control effects. Generally, the presence of oats or weeds reduced quality, with herbicide, untreated, and 11 kg ha^{-1} treatments produced first cut crude protein levels of 18, 14, and 10%, respectively.

Alfalfa establishment was most favorable when oat seeding rates were reduced as moisture was reduced.

1 | INTRODUCTION

A critical component of profitable alfalfa (*Medicago sativa* L.) production is the need to establish a dense, vigorous stand. One strategy for alfalfa establishment is planting a small grain with alfalfa as a companion or nurse crop. Companion crops can improve weed control and forage yield, and can help protect developing seedlings during alfalfa establishment (Hoy et al., 2002; Spandl, Kells, & Hesterman, 1999; Wollenhaupt, Bosworth, Doll, & Undersander, 1995). However, companion crops can be aggressive competitors with seedling alfalfa, resulting in a stand with reduced vigor, yield, nutritive value, and longevity (Curran et al., 1993; Hoy et al., 2002; Peters, 1961; Sheaffer et al., 2014). Though once widely used, companion crops fell out of favor in recent decades due to the development and widespread use of herbicides to control weeds in seedling alfalfa (Tesar & Jackobs, 1972). Recently, renewed interest in companion crops has emerged due to new marketing opportunities (like organic and oat-alfalfa mixed hay), onset of herbicide resistant weeds, interest in cover crops and soil health, need for emergency forage, and others.

During the early to mid-1900's, it was common for oats (*Avena sativa* L.) or barley (*Hordeum vulgare*) to be sown with alfalfa at rates of 56 to 84 kg ha^{-1} (Peters, 1961). Research on seeding rates of oat companion crops seeded with alfalfa is very limited and outdated. Smith et al. (1954) investigated companion seeding rates in oats from 18 to 108 kg ha^{-1} in Wisconsin and found that alfalfa stand densities decreased as seeding rates increased. Lanini et al. (1991) published the most recent work on oat companion crop seeding rates in alfalfa. In this study, rates from 0 to 36 kg ha^{-1} were evaluated and they determined that a seeding rate of 18 kg ha^{-1} provided the best combination of weed suppression and high forage yield. This study was conducted in California in fall-seeded alfalfa, which is a less common alternative to spring seeding in Utah and many other states. In the fall, both alfalfa and oats grow differently than they do in the spring in response to cooling temperatures and waning daylight hours that exist in the fall. (Tesar & Jackobs, 1972). Both studies agree that alfalfa establishment is more successful when oat companion crop seeding rates are reduced.

A challenge in using companion crops is selecting a seeding rate that balances the need for maximum forage yield and weed suppression while causing minimal harm to the alfalfa. A great deal of variability exists in seeding rate recommendations in extension publications across the U.S. Some recommend seeding an oat companion crop at a relatively high rate of 39 to 56 kg ha^{-1} (Shewmaker & Cheyney, 2007; Undersander et al., 2011), while others have adopted lower seeding rates of 22 to 34 kg ha^{-1} (Dixon et al., 2005; Islam et al., 2013; Putnam et al., 2012; Smith et al., 1996). Since the research is dated (most recent being 30 years old), and recommendations vary by state, additional research is needed to provide clarity into the oat companion crop seeding rates that maximize weed suppression and forage yield and minimize the effect on alfalfa stand establishment.

Companion crops compete with developing alfalfa seedlings for light, nutrients, and space, but competition for moisture is often the most concerning, particularly in semi-arid areas such as Utah. Mature alfalfa is very drought tolerant (Frate et al., 1991), and water use efficiency can increase as alfalfa stands age (Lindenmayer et al., 2011). However, seedlings are not drought tolerant, and reductions in water availability during establishment can reduce stand density (Rumbaugh et al., 1984). Some studies have reported that alfalfa is further suppressed by the presence of an oat companion crop when soil moisture is limited (Peters, 1961; Smith et al., 1954); however, it has also been observed that oats can cause more harm to seedling alfalfa at higher soil moisture levels due to competition for light (Janson & Knight, 1973). All the observations that have been recorded regarding companion crops and drought stress have been made based on comparisons between sites with differing moisture stress levels. No studies have compared alfalfa stand establishment with and without a companion crop at different irrigation levels in a single experiment.

Additionally, more work is needed to determine the optimal companion crop seeding rates at different levels of soil moisture. Optimal seeding rates of small grains can vary based on available soil moisture; higher population densities can be supported by higher soil moisture (Stark, 2007). How the small grain seeding rate should be adjusted when used as a companion crop with alfalfa at different moisture levels is unknown. Competition between alfalfa seedlings and the companion crop may be more intense at higher seeding rates when moisture is limited. More research is needed to determine if seeding rate recommendations should vary based on expected available soil moisture.

The objectives of this study were to determine the influence of oat companion crop seeding rates compared to the non-treated control (weedy and weed-free) at different irrigation levels on alfalfa stand establishment, weed suppression, and forage yield and nutritive value.

2 | MATERIALS AND METHODS

2.1 | Site Description and Experimental Design

Experiments were conducted in adjacent fields in 2019 and 2020 at the Utah State University Greenville Agricultural Research Farm, near North Logan, UT (41°45'55.55"N 111°48'56.22"W; 1402 m elevation) Soils in both years were a Millville silt loam (coarse-silty, carbonatic, mesic Typic Haploxeroll), with 21 g kg^{-1} organic matter and a 7.9 pH. The previous crops were wheat (*Triticum*) and quinoa (*Chenopodium quinoa*) in 2019 and 2020, respectively, and both sites were under conventional tillage.

The trial was designed to use a line-source irrigation method with a single sprinkler line through the center of the trial as described by Hanks, Keller, Rasmussen, and Wilson (1976). Six replicate blocks were sown in a randomized complete block design. Oat seeding rate and herbicide treatments were situated perpendicular to the irrigation line, and irrigation treatments were situated parallel to the irrigation line. Plot size was 1.52 by 2.74 m with 0.76 m borders between irrigation levels (ILs) and 0.46 m between seeding treatments.

2.2 | Planting

Experiments were planted on 8 May 2019 and 7 May 2020. Alfalfa and oats were sown using a drill (Model 3P600-1106, Great Plains Ag, Salina, KS) with double disk openers spaced 15 cm apart. Seeding rate treatments consisted of oats planted at rates of 89, 45, 22, 11, and 0 kg ha^{-1}, equivalent to 286, 144, 72, 36, and 0 seeds m^{-2}, - respectively. Oats were sown traveling perpendicular to the irrigation line. Alfalfa was sown traveling parallel to the irrigation line. Because of differing field conditions at the time of planting between years, alfalfa was sown at rates of 28 kg ha^{-1} in 2019 and 22 kg ha^{-1} in 2020. Alfalfa and oats were sown at a depth of 0.6 and 3.8 cm, respectively. Alfalfa variety 'Legendairy XHD' and oat variety 'Monida' were sown at both sites. The 2020 site was uniformly irrigated as needed to initiate uniform germination in all plots due to the lack of spring rain, while in 2019, alfalfa emerged with timely rainfall.

Only broadleaf weeds were present in 2019, so 2,4-DB (2,4-dichlorophenoxy butyric acid) herbicide at a rate of 1.12 kg ai ha^{-1} with a non-ionic surfactant (NIS) at 1% v/v was applied to plots designated for herbicide application. In 2020, both grass and broadleaf weeds were present, so clethodim (2-[(*E*)-*N*-[(*E*)-3-chloroprop-2-enoxy]-*C*-ethylcarbonimidoyl]-5-(2-ethylsulfanylpropyl)-3-hydroxycyclohex-2-en-1-one) at a rate of 0.28 kg ai ha^{-1} was added to 2,4-DB plus NIS. Applications were made when weather conditions were within label guidelines to avoid drift and volatility. Applications each year were made when alfalfa was in the 3rd trifoliate stage.

Irrigation treatments were applied using a line-source design described by Hanks et al. (1976). A single hand line with sprinklers (Model R33 Rotator®, Nelson Irrigation Corporation, Walla Walla, WA) located every 6 m was located perpendicular to seeding rate and herbicide treatments. Non-draining gaskets were installed at all pipe joints, and a 15 cm deep trench was excavated where the pipe was placed to prevent run-off from the irrigation line into plots. Seeding and herbicide treatments were divided into five 2.74-m-long subplots or ILs. Each irrigation level was separated by a 0.76 m alley. Plots with the designation IL 5 lay nearest to the sprinkler line, and plots with designation IL 1 were situated furthest from the irrigation line (Table 2-2). The amount of water applied to the plots decreased as the distance from the irrigation line increased. Thus, IL 5 received the most water, and IL 1 received the least amount of water. Rain gauges were placed at each IL, and the water applied was recorded following each irrigation event. Soil moisture at IL 5 was kept within non-yield-limiting ranges based on information received from a soil moisture sensor (Tereos 10 sensor, Meter, Pullman, WA). Water applied at each IL is expected to differ each year depending on environmental conditions. This method of irrigation application does not allow for randomized water levels and results in a restriction on randomization of ILs to plots. As such, statistical analyses and interpretation of the results from this method had constraints that are described in the statistical methods section below.

First cut of the forage occurred when oats reached soft dough stage (Brink & Marten, 1986), while second cut was taken when alfalfa in IL 5 reached bud stage. Harvest occurred in 2019 for first and second cut on 24 July 2019 through 26 July 2019 and 4 September 2019 through 6 September 2019, respectively. Harvest in 2020 for first and second cut occurred on 4 August 2020 through 6 August 2020 and 29 September 2020 through 1 October 2020, respectively.

Hand clippings were collected from each plot from three 645 cm^2 quadrats at a 5 cm stubble height and combined into one sample. Each sample was separated into alfalfa, oat, and weed components. Separated alfalfa stems were then counted to determine alfalfa stem density in each plot. Separated samples were then placed into a paper bag and dried to a constant weight at 60°C and weighed to determine herbage mass (as dry matter). After hand sampling, each plot was harvested at a 5 cm stubble height using a self-propelled forage harvester (HEGE 212, Wintersteiger AG, Ried im Innkreis, Austria).

Dried samples were initially ground with a Wiley Mill and finally with a cyclone mill to pass through a 1mm screen. Samples were scanned using a Near-Infrared Reflectance Spectrophotometer (NIRS; Model 6500 FOSS NIRSystems, Silver Springs, MD) following methods described by Martin, Shenk, and Barton (1989). The samples were analyzed using equations developed by the NIRS Consortium. The legume hay equation was used to analyze alfalfa (Legume Hay Calibration, 20LH50.eqa. release February 2020. Forage and Feed Testing Consortium, Hillsboro, WI. Constituents used: crude protein (CP), Neutral Detergent Fiber (NDF), in vitro true dry matter digestibility at 48 hours (IVTDMD48), and Starch), grass hay to analyze oats (Grass Hay Calibration, 20GH50.eqa. release February 2020. Forage and Feed Testing Consortium, Hillsboro, WI. Constituents used: CP, NDF, Fat, IVTDMD48, Starch), and mixed hay to analyze weeds (Mixed Hay Calibration, 20MH50.eqa. release February 2020. Forage and Feed Testing Consortium, Hillsboro, WI. Constituents used: CP, NDF, IVTDMD48, Starch). The quality content of each component (i.e. alfalfa, oats, and weeds) was analyzed separately to most accurately quantify the overall quality by utilizing different equations that were most closely associated with each separated forage.

The overall quality of the alfalfa, oat, and weed mixture was estimated by applying the quality content of each component at their respective proportions. Total dry matter yield (DMY) was estimated by adjusting the whole plot yield from the harvester to a dry matter basis, and then by adding the mass of the dried samples from that plot. The complete plot forage yield was then converted from kg $plot^{-1}$ to kg ha^{-1}. Alfalfa, oat, and weed DMY was estimated by applying the total DMY to the sample proportion of the respective component masses to total mass.

2.3 | Statistical Analysis

Data were analyzed using the ASReml-R package (Butler, Cullis, Gilmour, Gogel, & Thompson, 2017) of R (R Core Team, 2017). Dependent variables were alfalfa stem density, total dry matter yield (DMY), alfalfa DMY, oat DMY, weed DMY, crude protein (CP), neutral detergent fiber (NDF), in vitro dry matter digestibility at 48 hours (IVTDMD 48), and starch. The main effects of year, cut, IL, and seed treatment, and their corresponding interactions were considered fixed effects. The year main effect was considered fixed because the study encompassed only two years, which are insufficient to make meaningful variance conclusions. Block and its interactions with the other main effects were considered random. The 'rcov' command was used to control for spatial variation within the study. This also allowed for analysis across ILs despite the restriction on randomization because of the placement of the irrigation line (Wolfinger, Miles-McDermott, & Kendall, 1992). Based on an overall analysis across all main and interaction effects for each dependent variable, the main and interaction effects were consistently different from zero (Table 2-3). In particular, the cut × IL × seed treatment effect consistently differed from zero. Thus, the analyses were re-run across both years of the study, but within each cut and IL. Least significant difference mean separations were conducted at $\alpha = 0.05$.

3 | RESULTS AND DISCUSSION

3.1 | Irrigation, Weather, and Weeds

Utah is a semi-arid, high desert environment typified by cold, wet winters and hot, dry summers. Air temperatures during both years of the experiment were generally similar to long-term averages (Table 2-1). Precipitation during the 2019 growing season was higher than normal, with above average precipitation in March, April, May, and Sept. In contrast, precipitation was lower than normal in the 2020 growing season, with April and May exceptionally dry, which lead to a dry soil profile at planting. Consequently, applied irrigation was substantially higher in 2020 than 2019 (Table 2-2). In both years, water applied through irrigation was reduced in quantity as the distance from the irrigation line increased.

Weeds were present in all irrigation environments and, to some extent, all treatments. The predominant weeds species present at both cuts were common lambsquarters (*Chenopodium album L.*), redroot pigweed (*Amaranthus retroflexus L.*), kochia (*Bassia scoparia L.*), and green foxtail (*Setaria viridis [L.] P. Beauv.*). Green foxtail only occurred in 2020, and all other species were present in both years.

3.2 | Alfalfa Stem Density

Alfalfa stand establishment can be more accurately assessed with stem density than plant density due to the difficulty in distinguishing individual alfalfa plants without destructive sampling (Simmons, Scheaffer, Rasmussen, Stuthman, & Nickel, 1995). Alfalfa stem density was influenced by the seeding rate of the oat companion crop sown with alfalfa, and the response differed by cutting (Table 2-3). At first cutting, within the 0 kg ha^{-1} seeding rate treatment and regardless of IL, application of herbicide to control weeds in seedling alfalfa resulted in greater alfalfa stem density than the non-treated check (Table 2-4). Planting no companion crop (0 kg ha^{-1} seeding rate treatment) always resulted in higher alfalfa stem density than the next closest seeding rate (11 kg ha^{-1}), except at IL 5 where there was no difference. These findings agree with previous work that reported greater alfalfa stand density through chemical weed control in seedling alfalfa than alternative strategies such as no weed control or use of a companion crop (Hoy et al., 2002). Stem density decreased across all ILs as oat seeding rate increased. In general, first cut alfalfa stem density at the 89 kg ha^{-1} oat seeding rate was not different from the 45 kg ha^{-1} rate but was reduced from stands at lower seeding rates (11 and 22 kg ha^{-1}).

A reduction in stand density with increasing oat companion seeding rate has been reported in other studies (Lanini et al., 1991; Smith et al., 1954). However, data from this study suggests that the effect of a companion crop seeding rate may change based on available soil moisture. Developing alfalfa seedlings compete with other plants for water, nutrients, sunlight, and space. The effect of water availability appears to be significant, because the high irrigation treatment (IL 5) was the only IL without an alfalfa stem density reduction by increasing the oat seeding rate from 0 to 11 kg ha^{-1}. Furthermore, although the general trend of reduced stem density with increasing seeding rate was true across ILs at first cutting, the magnitude of the effect was greater as soil moisture decreased (Table 2-4). In ILs that received higher irrigation (IL 3 and 5), there was a 2- to 3-fold increase in stem density when oat seeding rate was reduced from 89 to 0 kg ha^{-1}. In contrast, ILs with lower irrigation (ILs 1-2) suffered a 6- to 7-fold reduction in alfalfa stem density at those same seeding rates. These data suggest that adequate soil moisture may help to mitigate the negative stand density effects of companion crops in seedling alfalfa. However, when soil moisture is limited, negative stand density effects can be amplified, particularly at higher oat seeding rates (22 to 89 kg ha^{-1}).

In ILs -2 and -3, the seeding rate response detected in first cut persisted into second cut (Table 2-4). In IL 3, the herbicide treatment applied to the 0 kg ha^{-1} oat seeding rate resulted in an increase in second cut alfalfa stem density compared to the control. The 0 kg ha^{-1} oat seeding rate treatment in IL 2, with or without herbicide, exhibited higher stem densities in cut 2 than any treatments with an oat companion crop sown. The results are similar to those of Hoy et al. (2002) where higher stand densities were realized with clear-seeded alfalfa than when grown with an oat companion crop. In both ILs -2 and -3, lower alfalfa stem densities were measured in higher oat seeding rates, suggesting the competitive nature of oats and weeds was more detrimental to alfalfa at these ILs. While weeds are not a major concern during establishment year for oat companion crops at high rates, both Chapko et al. (1991) and Hall et al. (1995) found that reductions in stand density, potentially caused by companion crops, can encourage weed growth in subsequent production years.

At second cut, no difference in alfalfa stem density was detected between seeding rate treatments in IL 1, 4, and 5 (Table 2-4). The effect of oat seeding rate on alfalfa stem density in the high irrigation treatments (IL 4 and 5) at first cut was small compared to the effect where less water was applied (IL 1-3). The combination of oats being removed by the action of cut 1 and the lack of moisture stress in IL 4 and 5 resulted in equal stem densities across all seeding rate treatments at second cut. A similar observation was made in California where much of the reduction in alfalfa stand density due to increased oat companion rates in the first cut lacked significance in subsequent cuts (Lanini et al., 1991). In contrast, (Janson & Knight, 1973) noted that oats competed more aggressively with alfalfa when soil moisture was adequate due to shading. At IL 1, the marginal lack of significance (P=0.07) in second cut stem density was most likely caused by the extreme lack of moisture during the hot summer months, adversely impacting alfalfa equally across treatments, regardless of oat seeding rate at establishment.

3.3 | Forage Dry Matter Yield

Dry matter yield is an important measure of the productivity of a field; lower yields generally imply lower productivity and, therefore, profit. In order to understand the composition of total DMY as a forage, the forage was separated into three components (alfalfa, oats, and weeds) with the total DMY being the sum of all components. Responses in total, alfalfa, oat, and weed DMY differed by cutting and were influenced by the oat companion seeding rate treatments (Table 2-3). Therefore, first and second cut are presented separately. First cut herbicide application influenced DMY. First cut total DMY was generally greater in the non-treated control (0 kg ha^{-1}) than herbicide treated plots (Table 2-5); however, over 55% of the total biomass was comprised of weeds (Table 2-5). At higher ILs (ILs 3 to 5), alfalfa DMY was consistently increased by the use of a herbicide compared to the non-treated control (36 to 39% alfalfa DMY increase). However, first cut alfalfa yields at low ILs (IL 1 and 2) were not improved by herbicide application, likely due to injury that may have occurred as a result of 2,4-DB application to alfalfa under moisture stress (Green & Legleiter, 2018).

In the first cut, differences were detected in total, alfalfa, and weed DMY between treatments sown with and without oats at most ILs (Table 2-5). In general, first cut total

DMY was increased by the presence of an oat companion crop. There was a 23 to 29% increase in total DMY by sowing a companion crop at the lowest rate (11 kg ha^{-1}) compared to the control (0kg ha^{-1}) in higher ILs (IL 4 and 5). However, treatment effects were more pronounced at lower ILs (IL 1 and 2) where the presence of an oat companion crop increased total DMY by approximately 60%. These data suggest that alfalfa seeded with an oat companion crop may be better able to maintain total DMY than solo-seeded alfalfa as soil moisture was reduced. However, the resilience of first cut total DMY to soil moisture reduction was accompanied by a reduction in alfalfa stand density at these low ILs. Other studies have consistently shown large reductions in alfalfa DMY when alfalfa is sown with oats instead of being sown alone (Lanini et al., 1991; Sulc et al., 1993). Alfalfa DMY during the first cut was diminished by the addition of a companion crop at all ILs. Oats, even when sown with alfalfa at the lowest rate (11 kg ha^{-1}), consistently reduced first cut weed DMY compared to the control by 50%. The ability of an oat companion crop to suppress weeds has been well documented (Hoy et al., 2002; Sheaffer et al., 2014; Spandl et al., 1999).

First cut total DMY differed between oat seeding rate treatments at all ILs (Table 2-5). Increased seeding rates generally resulted in an increase in total DMY. Higher forage yields by increasing oat companion seeding rates has been shown in other studies (Lanini et al., 1991; Smith et al., 1954). Unlike those findings, our results show that the magnitude at which yield increased by increasing oat companion seeding rates depended on soil moisture level. Oat seeding rates of 89 kg ha^{-1}, compared with the 11 kg ha^{-1} seeding rate, only increased total DMY slightly (by 19-26%) in higher ILs (IL 3-5). In contrast, at IL 1 and 2, there was a 35 to 50% total DMY increase when the seeding rate increased from 11 to 89 kg ha^{-1}.

First cut total DMY was comprised largely of oats, so oat DMY followed similar patterns as total DMY (Table 2-5). The dominance of the oat component in the mixture was expected due to its rapid growth compared to seedling alfalfa and the weed species present. In general, oat DMY in first cut increased as companion seeding rates increased.

Weed DMY at first cut varied in response to oat companion seeding rates (Table 2-5). Weed DMYs were consistently reduced by approximately 6-fold as oat rates were increased from 11 to 89 kg ha^{-1}. Weed suppression was similar between treatments where herbicide was applied and where oats were sown at high seeding rates (89 and 45 kg ha^{-1}). Those treatments reduced weed DMY by 88 to 90% regardless of IL. However, while low oat rates (11 and 22 kg ha^{-1}) did reduce weed DMY compared to the non-treated control (0 kg ha^{-1}), it was not reduced to the extent seen at high seeding rates.

Similar to reductions in weed DMY, alfalfa DMY was also reduced at higher oat seeding rates (Table 2-5). Generally, first cut alfalfa DMY was highest at low seeding rates. The response of alfalfa DMY to oat seeding rate also differed by IL. At IL 1, alfalfa DMY was similar across all oat companion seeding rates, while at all other ILs, alfalfa DMY decreased with increasing oat seeding rate. At that level, soil moisture may have been so depleted that oat seeding rate failed to influence the developing alfalfa seedlings.

Second cut alfalfa, weed, and total DMY differed between the herbicide-treated and non-treated control at all ILs (Table 2-6). In contrast to first cut, second cut alfalfa and total DMY in the herbicide treated plots was generally greater than the non-treated control. Furthermore, the suspected herbicide injury to alfalfa noted at low ILs in first cut did not persist into second cut. However, total DMY between the two treatments was similar because the presence of weeds in the non-treated control compensated for less alfalfa DMY.

Similar to first cut, the negative effects of using an oat companion crop were amplified in second cut as soil moisture was reduced. In most cases, the second cut alfalfa and total DMY differed in response to the use of a companion crop compared to solo-seeded alfalfa (Table 2-6). In higher ILs (IL 4 and 5), sufficient moisture for the needs of the crop resulted in only a 2 to 9% reduction in alfalfa DMY by the addition of a companion crop. These data show that alfalfa can rebound in second cut from the presence of a companion crop in first cut when soil moisture is not limiting. In contrast, under moisture stress, alfalfa DMY in second cut continued to lag when grown with a companion crop. At IL 3, the presence of a companion crop caused a 22% reduction in alfalfa yield, while reductions of 41 to 55% in alfalfa DMY were measured at the lowest ILs. These results suggest that, under moisture stress, the use of a companion crop in alfalfa at establishment could be devastating to the long-term productivity of the alfalfa stand; therefore, alfalfa planted under these conditions may be best sown without a companion crop. Second cut weed DMY response to treatments where oats were sown compared to the untreated check only differed in some cases (Table 2-6). At high ILs (IL 3-5) oats sown at 11 kg ha^{-1} did not reduce second cut weed DMY compared to the non-treated control but did reduce weed biomass at lower ILs (IL 1 and 2).

In second cut, oat seeding rates had variable effects on alfalfa, oat, weed and total DMY, depending on IL (Table 2-6). Total DMY was comprised mostly of alfalfa, so trends in alfalfa DMY generally mirrored that of total DMY. The effects of different oat seeding rates on total and alfalfa DMY were not different from each other at IL 5, suggesting that alfalfa was able to recover form first cut competition from the oat companion by second cut with adequate soil moisture. Comparably, the differences that did occur in total DMY at IL 3 and 4 were small. However, at the lowest ILs, seeding rates of oat companion crops became more important in determining second cut yield. In general, each incremental reduction in oat seeding rate increased both alfalfa and total DMY.

The oat regrowth that did occur in second cut was not a major component of the total forage yield (Table 2-6). Oat regrowth only differed from 0 in the 89 kg ha^{-1} oat seeding rate treatment in IL 4 and 5. Oats at those treatment levels were most likely at slightly earlier stages of maturity at the time of first cut, since oat regrowth declines as the maturity of the companion crop increases. (Klebesadel & Smith, 1960).

Although oats were removed at first cut, the earlier presence of oats continued to suppress weeds at second cut. In general, second cut weed DMY was reduced by higher oat seeding rates across ILs (Table 2-6). Weed reductions caused by the former presence of oats is not unique to this study (Chapko et al., 1991; Hall et al., 1995; Spandl et al., 1999).

3.4 | Forage Quality

The interaction between oat seeding rate treatments and cut affected all quality measures; therefore, responses to cut were presented separately (Table 2-3). Animals that consume forages such as alfalfa and oats require protein to perform their various tasks including weight gain, milk production, maintenance, and energy expenditures. Protein is most commonly analyzed in forages by a measure of crude protein (CP), which is simply a measure of % nitrogen multiplied by 6.25. In general, first cut CP was higher in herbicide treated plots than the non-treated control across all ILs due to the absence of weeds (Table 2-7). Oats are lower in CP than alfalfa, so the addition of oat as a companion crop reduced CP in the total forage 27 to 40% compared to the non-treated control. Oat seeding rates between 89 and 11 kg ha^{-1} influenced CP. Crude protein generally declined as oat rates increased, regardless of IL. Second cut CP did not differ for any treatment at any IL except IL 3 (Table 2-8), where differences were relatively small but may have been related to lack of weed suppression in some treatments.

Neutral detergent fiber (NDF) is a measure of fiber in a plant. Lignin, hemicellulose, and cellulose, which are the building blocks of cell walls, are all included in an NDF measure. Lower NDF values are usually desired and are an indicator of younger, more palatable plants. Within the 0 kg ha^{-1} seeding rate, herbicides reduced first cut NDF to less than 85% of the untreated check at all ILs (Table 2-7). Oats are high in cell wall components, so large increases in NDF were observed in treatments where oats were sown with alfalfa. Additionally, increased soil moisture can somewhat mitigate increased NDF with companion crops compared to solo-seeded alfalfa. At high ILs (IL 4 and 5), NDF increased less than 19% when an oat companion was seeded with alfalfa but elevated to 37 to 40 % at lower ILs (IL 1 and 2). Weeds are similar to oats as they can be higher in cell wall components than alfalfa. Oats seeded at different rates generally did not influence first cut NDF. Second cut NDF did not usually differ by oat seeding rate, but differences did exist between high oat seeding rates and solo-seeded alfalfa (Table 2-8). This trend in NDF has also been observed by Hoy et al. (2002). Alfalfa impacted by the prior presence of an oat-companion crop tended to be in earlier stages of development at the time of second cut; therefore, lower NDF was expected in treatments where companion crops were present in the previous cutting. This observation was confirmed in IL 4 and 5 where NDF was lower among treatments where oats were sown than without (Table 2-8).

In vitro true dry matter digestibility at 48 hours (IVTDMD48) is a measure of digestibility that estimates the percentage of a forage that can be digested by a cow. In a lab, IVTDMD48 can be measured by incubating forage, rumen fluid, and buffer solution together for 48 hours. Values are presented as a percentage of the biomass that can be digested, so higher values are desired since they imply that the forage is more digestible. First cut IVTDMD48 was impacted by the presence of an oat companion crop, even at the lowest seeding rate at most ILs, but differences in IVTDMD48 were not generally detected between oat companion seeding rates (Table 2-7). This result is due to the fact that oat stems and leaves are less digestible than those of alfalfa. Differences in second cut IVTDMD48 were found between treatments in ILs 2 and 3 (Table 2-8). At these levels, solo-seeded alfalfa plus herbicide was slightly higher in second cut IVTDMD48 than most other seeding treatments. Large amounts of weeds among treatments at those ILs are the most likely cause of differences in IVTDMD48.

Starch is an energy form that is usually more common in the grain than in the stems and leaves of a plant. Starch should be expected to be higher in treatments where there is more grain production. The 0 kg ha^{-1} oat seeding rate with or without herbicide did not change the amount of starch available in the forage at first cut (Table 2-7). A predictable starch response occurred by the addition of the oat companion crop to alfalfa. This response increased starch by 2-fold when companion crops were added compared to solo-seeded alfalfa. Starch levels were influenced by oat companion seeding rates. Higher levels of starch were generally found at high oat seeding rates. Starch differences in response to IL did not generally occur, and no responses in starch were usually measured among treatments in the second cut (Table 2-8).

4 | CONCLUSIONS

Alfalfa stem density in the first cutting was reduced as oat seeding rate was increased. Total DMY increased with the addition of a companion crop and as oat seeding rate was increased. Weeds and alfalfa were both reduced in first cutting by the addition of a companion crop. Weeds were also reduced in second cut with high oat seeding rates (45 and 89 kg ha^{-1}). Similar responses at all ILs were found when the oat seeding rate of 89 kg ha^{-1} was split by half (45 kg ha^{-1}). As ILs declined, oats had a larger impact on yield and alfalfa stem density, and competition from weeds and oats became more severe. Quality was reduced when weeds or oats were a component of the forage, and quality reduction was evident as seeding rate was increased. However, plots where oats were present produced higher starch levels. At high ILs, alfalfa stem densities in the second cutting were not reduced, but alfalfa yield was.

These data suggest that solo-seeded alfalfa with a herbicide application can be the best method to achieve consistently high alfalfa stem densities and high forage nutritive value, regardless of soil moisture conditions. When herbicides cannot be used (such as organic production), an oat companion crop may be preferred over solo-seeded alfalfa in high soil moisture conditions. However, when soil moisture is limited, alfalfa sown alone may be best to maximize stem density, alfalfa yield, and quality. A producer may prefer an alfalfa-oat forage mixture for marketing, to feed to livestock on a maintenance diet, or when highly erodible soils are a major concern, despite the disadvantages of companion crops in alfalfa establishment. In these situations, higher rates (>22 kg ha^{-1}) can be successful when soil moisture is adequate. However, lower rates of 11 to 22 kg ha^{-1} may be advised to mitigate the risk of alfalfa establishment failure. If companion crops are desired in low soil moisture conditions, results here suggest that oat seeding rates between 0 and 11 kg ha^{-1} may be best for alfalfa stand establishment, and rates beyond 22 kg ha^{-1} should be avoided.

TABLE 2-2 Precipitation and average monthly air temperatures in 2019 and 2020 at the Utah State University Greenville Farm near North Logan, UT.

	Air Temperature[a]			Precipitation		
Month	2019[b]	2020	2019-1991	2019	2020	30-yr
	———°C———			———mm———		
April	8.9	8.3	8.3	85.3	17.5	51.0
May	12.2	13.9	13.1	74.8	21.3	64.1
June	17.8	16.7	18.3	4.9	66.3	35.5
July	22.8	22.2	23.2	8.6	3.8	20.4
August	21.7	23.3	22.6	4.5	3.0	21.2
September	15.6	15.6	16.7	110.0	11.9	39.5
Annual[c]	8.3	8.4	9.1	576.8	269.8	503.6

[a] Weather data obtained using a Utah Climate Center weather station centrally located within 1km of the experimental sites.

[b] Average temperature and total precipitation for each standard month period of Oct. through Sept. of the planting year.

TABLE 2-3 Applied irrigation water per irrigation level (IL) calculated as amount applied per day during the 2019 and 2020 growing seasons from planting to first cut and from first cut to second cut.

Irrigation Level	**Irrigation**		**Precipitation**[a]	
	2019	**2020**	**2019**	**2020**
	mm d^{-1}			
	First Cut [b]			
IL 1	0	0.03	0.88	1
IL 2	0.53	0.37	0.88	1
IL 3	1.79	1.85	0.88	1.00
IL 4	1.89	3.27	0.88	1.00
IL 5	1.91	3.87	0.88	1.00
	Second Cut			
IL 1	0.04	0	0.28	0.27
IL 2	0.26	0.13	0.28	0.27
IL 3	0.53	0.62	0.28	0.27
IL 4	0.63	1.51	0.28	0.27
IL 5	0.75	1.79	0.28	0.27

[a] Precipitation data obtained using a Utah Climate Center weather station central to both sites.
[b] See Materials and Methods for harvest dates.

TABLE 2-4 Sums of squares associated with main and interaction effects for stem density, total, alfalfa, oat, and weed dry matter yield, crude protein (CP), Neutral Detergent Fiber (NDF), Fat, In Vitro Dry Matter Digestibility 48 (IVTDMD48), and starch at five irrigation levels (IL), six seeding treatments (S), two cuts, and two years.

		Alfalfa Density	**Dry Matter Yield**				**Quality Component**			
Source	**df**	**Stems m^{-2}**	**Total**	**Alfalfa**	**Oat**	**Weed**	**CP**	**NDF**	**IVTDMD 48**	**Starch**
		Sums of Squares								
Year (Y)	1	428***	175***	46***	1	4*	139***	583***	3	53***
Cut (C)	1	82***	201***	323***	621***	90***	612***	1427***	25***	39***
Irrigation Level (IL)[a]	4	260***	839***	871***	1	46***	39***	307***	29***	4
Seeding Treatment(S)	5	479***	29***	876***	21***	337***	1579***	535***	405***	53***
Y:C	1	72***	19***	53***	0	62***	11**	4*	20***	970***
Y:IL	4	16**	23***	22***	11*	48***	2	25***	11*	13**
C:IL	4	50***	33***	95***	110***	81***	14**	25***	67***	50***
Y:S	5	313***	6	229***	29***	5	161***	35***	15*	161***
C:S	5	59***	785***	110***	1262***	278***	768***	659***	32***	145***
IL:S	20	36*	43**	468***	34*	72***	82***	42**	75***	73***
Y:C:IL	4	8	11*	18**	6	12*	24***	18**	10*	33***
Y:C:S	5	8	32***	24***	10	169***	58***	23***	15*	662***
Y:IL:S	20	50***	78***	86***	28	66***	46***	20	24	29
C:IL:S	20	21	43**	260***	158***	128***	52***	34*	58***	55***
Y:C:IL:S	16	23	34*	84***	28	39**	23	14	17	22

* Significant at the 0.05 probability level (P < 0.05). ** Significant at the 0.01 probability level (P < 0.01). *** Significant at the 0.001 probability level (P < 0.001).

[a] Sums of squares due to IL should be interpreted with caution because plots assigned to IL are not randomized within replications.

TABLE 2-5 Alfalfa stem density (stems m^{-2}) of six alfalfa-companion crop treatments evaluated at five irrigation levels (ILs) for first and second cut at North Logan, UT during 2019 and 2020. See table 1 for irrigation application volumes (IL 1 < IL 2 < IL 3 < IL 4 < IL 5).

Irrigation Level	Oat Seeding Rates[a]							
	89 kg ha^{-1}	45 kg ha^{-1}	22 kg ha^{-1}	11 kg ha^{-1}	0 kg ha^{-1}	0 kg ha^{-1} +Herbicide	LSD	P-value
	Stems m^{-2}							
	Cut 1							
IL 1	109d[b]	172d	279c	320c	606b	818a	104	$< 2{\cdot}10^{-16}$
IL 2	103d	250d	468c	526c	744b	992a	149	$< 2{\cdot}10^{-16}$
IL 3	372d	499d	711c	676c	955b	1239a	173	$< 2{\cdot}10^{-16}$
IL 4	480d	606d	769c	834c	985b	1258a	133	$< 2{\cdot}10^{-16}$
IL 5	504d	694c	713c	802bc	939b	1264a	170	$< 2{\cdot}10^{-16}$
	Cut 2							
IL 1	506	443	552	641	748	854	NS[c]	0.07
IL 2	311c	612b	697b	680b	939a	1083a	175	$< 2{\cdot}10^{-16}$
IL 3	1173bc	1046c	1246b	1247b	1201bc	1472a	218	0.008
IL 4	1193	1318	1174	1315	1320	1392	NS	0.25
IL 5	1278	1113	1278	1265	1257	1323	NS	0.73

[a] Alfalfa seeding rates (28 kg ha^{-1} in 2019 and 22 kg ha^{-1} in 2020) were held constant across oat seeding rates.
[b] Numbers in the same row with the same letter are not statistically different.
[c] Not statistically significant (P > 0.05).

TABLE 2-5 First cut alfalfa, oats, weeds, and total dry matter yield (kg ha^{-1}) of six alfalfa-companion crop seeding treatments evaluated at five irrigation levels (ILs) in North Logan, UT during 2019 and 2020. See table 1 for irrigation application volumes (IL 1 < IL 2 < IL 3 < IL 4 < IL 5).

Forage Component	Oat Seeding Rates[a]							
	89 kg ha^{-1}	**45 kg ha^{-1}**	**22 kg ha^{-1}**	**11 kg ha^{-1}**	**0 kg ha^{-1}**	**0 kg ha^{-1} +Herbicide**	**LSD**	**P-value**
	kg ha^{-1}							
IL 1								
Alfalfa	123c[b]	55c	181bc	191bc	433a	294ab	158	$4 \cdot 10^{-5}$
Oat	5593a	4739a	3565b	2357c	0d	0d	1043	$< 2 \cdot 10^{-16}$
Weed	294bc	80cd	257bcd	425b	839a	5d	282	$6 \cdot 10^{-8}$
Total	6010a	4875b	4003bc	2973c	1282d	299d	1038	$< 2 \cdot 10^{-16}$
IL 2								
Alfalfa	41d	100cd	226cd	391bc	902a	588b	306	$2 \cdot 10^{-8}$
Oat	6224a	5447a	4263b	2826c	0d	0d	941	$< 2 \cdot 10^{-16}$
Weed	76cd	186cd	469bc	859b	1721a	4d	398	$< 2 \cdot 10^{-16}$
Total	6340a	5733ab	4958bc	4074c	2624d	592e	993	$< 2 \cdot 10^{-16}$
IL 3								
Alfalfa	101e	294de	578cd	805c	1443b	2369a	432	$< 2 \cdot 10^{-16}$
Oat	7932a	6567ab	5121b	3552c	0d	0d	1479	$< 2 \cdot 10^{-16}$
Weed	247d	511cd	960c	2162b	4352a	38d	566	$< 2 \cdot 10^{-16}$
Total	8279a	7372ab	6658bc	6519bc	5795c	2407d	1347	$< 2 \cdot 10^{-16}$
IL 4								
Alfalfa	380d	287d	632d	1113c	2640b	4149a	477	$< 2 \cdot 10^{-16}$
Oat	10541a	8003b	7339b	5739c	0d	0d	1368	$< 2 \cdot 10^{-16}$
Weed	232c	335c	1146b	1304b	3652a	79c	435	$< 2 \cdot 10^{-16}$
Total	11153a	8625b	9117b	8156b	6291c	4228d	1289	$< 2 \cdot 10^{-16}$

IL 5								
Alfalfa	179e	401de	659d	1156c	2696b	4477a	360	$< 2\cdot10^{-16}$
Oat	11156a	10032a	8166b	6267c	0d	0d	1319	$< 2\cdot10^{-16}$
Weed	316c	373c	1291b	1942b	3933a	54c	685	$< 2\cdot10^{-16}$
Total	11650a	10826ab	10117bc	9366c	6629d	4543e	923	$< 2\cdot10^{-16}$

[a] Alfalfa seeding rates (28 kg ha^{-1} in 2019 and 22 kg ha^{-1} in 2020) were held constant across oat seeding rates.

[b] Numbers within each row with the same letter designation are not statistically different.

TABLE 2-6 Second cut alfalfa, oats, weeds, and total dry matter yield (kg ha^{-1}) of six alfalfa-companion crop seeding treatments evaluated at five irrigation levels (ILs) in North Logan, UT during 2019 and 2020. See table 2-1 for irrigation application volumes (IL 1 < IL 2 < IL 3 < IL 4 < IL 5).

Forage Component	Oat Rates[a]							
	89 kg ha^{-1}	45 kg ha^{-1}	22 kg ha^{-1}	11 kg ha^{-1}	0 kg ha^{-1}	0 kg ha^{-1} +Herbicide	LSD	P-value
	kg ha^{-1}							
IL 1								
Alfalfa	69b[b]	67b	141b	359b	791a	995a	368	$1 \cdot 10^{-8}$
Oat	2	12	40	9	0	0	NS[c]	0.78
Weed	6b	10b	42b	41b	158a	25b	73	0.001
Total	76b	89b	223b	409b	949a	1020a	379	$4 \cdot 10^{-9}$
IL 2								
Alfalfa	131e	449d	495d	813c	1380b	1900a	314	$< 2 \cdot 10^{-16}$
Oat	23	55	36	21	0	0	NS	0.06
Weed	58c	180bc	139bc	263b	538a	45c	191	$1 \cdot 10^{-6}$
Total	212d	684c	670c	1097b	1918a	1945a	298	$< 2 \cdot 10^{-16}$
IL 3								
Alfalfa	1301d	1691cd	2113bc	1989c	2574b	3169a	533	$2 \cdot 10^{-11}$
Oat	167	112	57	15	0	0	NS	0.11
Weed	121b	107b	223b	467a	669a	55b	202	$9 \cdot 10^{-11}$
Total	1589c	1910bc	2393b	2472b	3243a	3224a	574	$4 \cdot 10^{-10}$
IL 4								
Alfalfa	2692e	3240cd	2948de	3542bc	3599b	4306a	323	$< 2 \cdot 10^{-16}$
Oat	186a	107ab	8b	26b	0b	0b	117	0.006
Weed	256ab	110b	427a	375a	393a	71b	228	0.004
Total	3133c	3457c	3382c	3943b	3992b	4377a	362	$2 \cdot 10^{-12}$

IL 5								
Alfalfa	2976c	3307c	3258c	3425bc	3775b	4249a	452	$4 \cdot 10^{-7}$
Oat	259a	26b	0b	4b	0b	0b	134	0.0003
Weed	126b	165ab	229ab	335a	326a	50b	187	0.02
Total	3361c	3497c	3487c	3763bc	4100ab	4298a	471	0.0002

[a] Alfalfa seeding rates (28 kg ha^{-1} in 2019 and 22 kg ha^{-1} in 2020) were held constant across oat seeding rates.

[b] Numbers within each row with the same letter designation are not statistically different.

[c] Not significant ($P > 0.05$).

TABLE 2-7 First cut crude protein (CP), neutral detergent fiber (NDF), in vitro total dry matter digestibility (IVTDMD48), and starch of six alfalfa-companion crop seeding treatments evaluated at five irrigation levels (ILs) at North Logan, UT during 2019 and 2020. Quality values are presented as an unseparated forage[a]. See table 1 for irrigation application volumes (IL 1 < IL 2 < IL 3 < IL 4 < IL 5).

Irrigation Level	Oat Seeding Rates[b]							
	89 kg ha^{-1}	**45 kg ha^{-1}**	**22 kg ha^{-1}**	**11 kg ha^{-1}**	**0 kg ha^{-1}**	**0 kg ha^{-1} +Herbicide**	**LSD**	**P-value**
				%CP				
IL 1	8.3e[c]	8.3e	9.4d	10.6c	16.9b	21.2a	1.1	$< 2\cdot10^{-16}$
IL 2	8.0e	9.1de	9.6d	11.2c	18.9b	21.3a	1.3	$< 2\cdot10^{-16}$
IL 3	8.5e	9.0de	9.9d	11.9c	16.5b	22.1a	1.4	$< 2\cdot10^{-16}$
IL 4	7.0d	7.3d	9.1bc	11.0b	15.9a	17.7a	2.0	$< 2\cdot10^{-16}$
IL 5	6.8d	7.4d	8.2d	10.2c	14.8b	18.5a	1.4	$< 2\cdot10^{-16}$
				%NDF				
IL 1	51.4cd	52.4d	50.0cd	48.4c	33.1b	25.0a	3.5	$< 2\cdot10^{-16}$
IL 2	52.1d	52.4d	50.2d	46.6c	30.8b	24.4a	2.5	$< 2\cdot10^{-16}$
IL 3	50.1c	50.3c	49.3c	48.4c	35.8b	29.1a	3.7	$< 2\cdot10^{-16}$
IL 4	53.8c	52.9c	54.1c	51.0c	42.0b	35.7a	4.0	$< 2\cdot10^{-16}$
IL 5	54.0c	54.1c	54.9c	53.8c	43.1b	36.4a	3.9	$< 2\cdot10^{-16}$
				%IVTDMD48				
IL 1	69.5c	69.4c	70.3c	72.8c	82.6b	87.0a	3.6	$< 2\cdot10^{-16}$
IL 2	68.3b	70.6b	71.9b	72.3b	82.5a	85.0a	4.1	$< 2\cdot10^{-16}$
IL 3	67.7d	70.2cd	70.7cd	73.4bc	76.6b	83.4a	4.6	$1\cdot10^{-11}$
IL 4	67.7c	67.6c	69.9bc	70.8bc	77.6a	73.9ab	5.5	0.002
IL 5	68.2b	67.2b	68.7b	69.7b	75.7a	78.0a	2.9	$< 2\cdot10^{-16}$

	%Starch							
IL 1	9.8a	9.5a	8.5ab	8.0b	3.1c	2.8c	1.4	$< 2{\cdot}10^{-16}$
IL 2	10a	9.4ab	8.6b	7.1c	2.7d	3.0d	0.9	$< 2{\cdot}10^{-16}$
IL 3	8.3a	8.1a	6.8b	5.1c	2.3d	2.2d	0.8	$< 2{\cdot}10^{-16}$
IL 4	7.5a	7.4a	5.3b	5.0b	2.2c	2.2c	1.0	$< 2{\cdot}10^{-16}$
IL 5	8.1a	7.6a	5.7b	4.4b	2.0c	2.7c	0.8	$< 2{\cdot}10^{-16}$

[a] See materials and methods for details on forage quality analyses.

[b] Alfalfa seeding rates (28 kg ha^{-1} in 2019 and 22 kg ha^{-1} in 2020) were held constant across oat seeding rates.

[c] Mean values within each row with the same letter designation are not statistically different.

TABLE 2-8 Second cut crude protein (CP), neutral detergent fiber (NDF), in vitro total dry matter digestibility (IVTDMD48), and starch of six alfalfa-companion crop seeding treatments evaluated at five irrigation levels (ILs) at North Logan, UT during 2019 and 2020. Quality values are presented as an unseparated forage[a]. See table 1 for irrigation application volumes (IL 1 < IL 2 < IL 3 < IL 4 < IL 5).

Irrigation Level	Oat Seeding Rates[b]							
	89 kg ha^{-1}	45 kg ha^{-1}	22 kg ha^{-1}	11 kg ha^{-1}	0 kg ha^{-1}	0 kg ha^{-1} +Herbicide	LSD	P-value
				%CP				
IL 1	-[c]	-	-	17.9	17.1	18.4	NS[d]	0.74
IL 2	-	-	17.1	16.3	16.5	20.0	NS	0.07
IL 3	20.0a[e]	18.5abc	17.1c	17.4bc	17.9bc	19.2ab	1.8	0.01
IL 4	19.5	19.4	18.6	19.0	18.2	18.0	NS	0.21
IL 5	19.0	19.2	19.0	19.0	17.9	18.0	NS	0.34
				%NDF				
IL 1	-	-	-	25.1	26.3	25.1	NS	0.09
IL 2	-	-	26.8a	30.5b	35.1c	25.2a	2.4	0.0001
IL 3	27.6	26.3	26.8	32.1	31.6	29.4	NS	0.07
IL 4	29.0a	29.8ab	32.5cd	31.8bc	32.9cd	34.4d	2.4	$7 \cdot 10^{-5}$
IL 5	31.8a	30.3a	31.0a	32.8ab	34.6b	34.2b	2.8	0.02
				%IVTDMD48				
IL 1	-	-	-	78.8	78.5	82.8	NS	0.31
IL 2	-	-	68.2b[b]	67.9b	68.7b	86.4a	7.0	0.002
IL 3	79.7ab	73.7bc	69.4c	75.0ab	76.8ab	81.5a	6.8	0.008
IL 4	78.5	79.9	79.8	79.9	80.2	78.6	NS	0.93
IL 5	80.6	81.0	80.2	80.7	78.9	80.5	NS	0.59

	%Starch							
IL 1	-	-	-	2.8	2.6	3.2	NS	0.55
IL 2	-	-	1.7bc	1.9b	1.4c	2.8a	0.3	0.0004
IL 3	2.3	2.0	2.2	2.3	2.3	2.6	NS	0.34
IL 4	2.6	2.7	2.9	2.6	2.9	2.8	NS	0.62
IL 5	3.0	2.9	2.9	2.6	2.8	3.1	NS	0.73

[a] See materials and methods for details on forage quality analyses.

[b] Alfalfa seeding rates (28 kg ha^{-1} in 2019 and 22 kg ha^{-1} in 2020) were held constant across oat seeding rates.

[c] Not enough volume was available in one or more component (alfalfa, weed, oat) to accurately estimate quality.

[d] Not significant ($P > 0.05$).

[e] Numbers within each row with the same letter designation are not statistically different.

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